第 12 卷　第 1 期
2004 年 2 月

光学 精密工程
Optics and Precision Engineering

Vol. 12　No. 1
Jan. 2004

**Article ID**　1004-924X (2004) 01-0001-05

# Use of diffractive-refractive optical system for correction of secondary spectrum

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**Abstract:** The secondary spectrum of an aerospace wide spectrum (420.0~900.0 nm) and long focus (450 mm) telescope was corrected by combining diffractive and refractive optical elements, and the structural dimensions of diffractive lens and the aberrations of a telescope system were calculated as well. Computer simulation results showed that the secondary spectrum of the telescope objective lens corrected by combining diffractive and refractive optical elements was no greater than 0.08 mm, and the position aberration of a point on the axis was also very small, and repeated elimination of aberration was achieved. The optical transmission function was generally close to the diffractive limit, and the whole system designed could satisfy the actual operational requirements.

**Key words:** diffractive optical system; refractive optical system; secondary spectrum; telescopes; correction
**CLC Number:** V447.1　**Document code:** A

# 衍/折射光学系统校正二级光谱的研究

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摘要: 将衍射和折射光学元件结合, 对星载用宽光谱 (420.0~900.0 nm)、长焦距 (450 mm) 望远物镜的二级光谱进行了校正, 计算了衍射透镜的结构尺寸和望远镜系统的像差。计算机模拟结果表明: 采用衍/折射混合校正后的望远物镜的二级光谱不大于 0.08 mm, 轴上点的位置色差也很小, 实现了复消色差, 光学传递函数也基本接近衍射极限。所设计的整个系统可以满足实用要求。

关　键　词: 衍射光学系统; 折射光学系统; 二级光谱; 望远镜; 校正
中图分类号: V447.1　　文献标识码: A

## 1　Introduction

Secondary spectrum can reduce the imaging quality and lower the contrast of image both in high accuracy telescopes system and microscopes application with wide field of view. Therefore, the removal of secondary spectrum is an important factor to evaluate the quality of optical system. In general, introducing the lenses combination with different materials properties (index and dispersion) can reduce visual secondary

**Received date:** 2003-06-14; **Revised date:** 2003-11-18
**Foundation item:** 国家"863"项目 (No. 2002AA782022); 国家自然科学基金项目 (No. 60278019); 陕西省自然科学基金重点项目 (No. 2000X08)

spectrum. For example, fluorite may be combined with suitable glass to eliminate or reduce the secondary spectrum. However, it is disadvantage for availability of big size of fluorite due to its fabrication process and high cost in big aperture telescope application. Practically, the application of binary optics lens (BOL) is more economic at low scale instead of fluorite. By using the special properties of BOLs related to the dispersion and wavelength, the effect of secondary spectrum can be reduced in a hybrid diffractive-refractive optical system. In addition, BOLs are used to ease optical design and improve the imaging quality of optical systems[1].

In reference[2-3] it was also reported to decrease secondary spectrum by means of BOL recently. But it was not commercialized yet. In this paper, the methods of hybrid diffractive-refractive lens was used to reduce secondary spectrum in paraxial long-focus length telescopes for aerospace application. The principles and design of BOLs were presented as well. Furthermore, optimization simulations of optical system were carried out with ZMAX and simulation results were desirable for practical applications.

## 2 Principle of apochromats of BOL

The lens used to remove the secondary spectrum are called as apochromats. Usually secondary spectrum can be reduced by using special dispersion combination of the negative lens and positive lens in conventional optical design. Note, however, that for some pairs, the difference of dispersion between negative lens and positive lens is small, and the powers of the individual elements required for achromatism are higher than with an ordinary pair of glasses. This increase in element power causes a corresponding increase in the other residual aberrations. For relative complex structures, the secondary spectrum may be reduced in terms of separation of two lenses. However, the achromat cannot be eliminated completely in a thin doublet system. In this paper, we use other way to solve this problem.

For visible lights, the index of the optical materials like glass and crystals will decrease with wavelength due to positive dispersion. The BOLs with positive focal power are negative dispersion, it can be used to correctdispersion, take over some focal power, and reduce monochromatic aberration.

### 2. 1 Properties of BOLs

According to the normal observation spectrum, the apochromat system for $D$ (587. 6 nm)、$C$ (656. 3 nm) and $F$ (486. 1 nm) lines is designed firstly.

The image of BOLs is formed like that of holographic optics. The corresponding focal length to each line are given as:

$$f_C = f_D(\lambda_D/\lambda_C),\ f_F = f_D(\lambda_D/\lambda_F)$$

Thus yield power are:

$$\varphi_C = (\lambda_C/\lambda_D)\,\varphi_D,\quad \varphi_F = (\lambda_F/\lambda_D)\,\varphi_D, \qquad (1)$$

where $f_C, f_D, f_F$ are the focal lengths of BOLs corresponding to the wavelengths of light $C$, light $D$ and light $F$ respectively. $\lambda_C$, $\lambda_D$, $\lambda_F$ are the wavelengths corresponding to light $C$, light $D$ and light $F$ respectively, $\varphi_C$, $\varphi_F$ are powers corresponding to light $C$ and light $F$ respectively.

The effective refractive index of BOL will be:

$$n_{z\,\mathrm{eff}} = 1 + 1/(c_0 f_z) = 1 + \lambda_z/(c_0 f_z \lambda_d)$$

According to classical optical materials, the Abbe number $\nu$ (inverse dispersions) is defined as

$$\nu_d = (n_d - 1)/(n_F - n_C)$$

We can obtain the effective Abbe number of BOL:

$$\nu_d^B = \{\lambda_d/(\lambda_F - \lambda_C)\} = -3.452.$$

The dispersion equation of BOL' s may be expressed as:

$$P_{\lambda_1\lambda_2} = (\lambda_1 - \lambda_2)/(\lambda_F - \lambda_C)$$

$$\lambda_F \leqslant \lambda_2 < \lambda_1 \leqslant \lambda_C, \qquad (2)$$

Where $P_{\lambda_1\lambda_2}$ stand for the dispersion from light 1 to light

2. From the Eq. (2) it is known the dispersion of BOL's depends on wavelength of the light, does not depend on the refractive index of glasses. Usually common optical materials are more dispersive at shorter wavelength, while less dispersive at longer wavelength. These two dispersion characteristics can be combined to make apochromats used in optical systems only by doublet of common optical materials. There still exists another question if achromatic triplet may be used for this purpose[7].

### 2. 2 Distribution of focal power of diffractive-refractive lens

For thin-len system, the net focal length of the three elements is $f$, and the focal lengths of these three optics are $f_a$, $f_b$, $f_c$ respectively, then[6]:

$$f_a = f' \Delta P(\nu_a - \nu_c)/(P_b - P_c)P_a$$

$$f_b = f' \Delta P(\nu_a - \nu_c)/(P_c - p_b)P_b$$

$$f_c = f' \Delta P(\nu_a - \nu_c)/(P_a - P_b)P_c, \qquad (3)$$

where $\nu_a$, $\nu_b$, $\nu_c$ are Abbe numbers of the three lenses respectively. $P_a$, $P_b$, $P_c$ are partial dispersion of the three lenses respectively. $\Delta P$ is the vertical distance of material b to the line connecting the plot of material a and c on graph $P$-$\nu$. It is positive when the plot of material b is above the line, otherwise, $\Delta P$ is negative. Furthermore, we can get

$$\Delta P = \{\nu_a(P_b - P_c) + \nu_b(P_c - P_a) + \nu_c(P_a - P_b\}/(\nu_a - \nu_c), \qquad (4)$$

It can be known from Eq. (3) and (4), with the same focal power, the bigger the absolute value of $\Delta P$ is, the smaller the focal power of every apochromat is, and the smaller surface curvature, In addition higher $\Delta P$ can ease design the apochromat and more ideal to remove the secondary spectrum by BOL.

## 3 Design of BOL

BOLs can be designed to get the effect of apochromats by the method reported in reference[6-7]. The design index of the system are given as:

net focal length: 450 mm, aperture: 100 mm, relative aperture: 4. 5 and for sight-field angle: 2.

The field is paraxial diffractive. Because the focal power of the system is fixed according to technical requirement, BOL will be designed by scaling theory of light propagation, optical amplitude and system focal length depend on the design of BOL. See below:

$$r_m = [(f_0 + m\lambda_d/j)^2 - f_0^2]^{1/2}(m = 1, 2, \cdots N), \qquad (5)$$

where $r_m$ is the radius of $m$-th. $m$ is the number of rings. $j$ is step numbers, $\lambda_d$ is main wavelength used for the fabrication of the BOL, $f_0$ is the main-wave focal length of BOL. When the $m$ is big enough, we can get $(m\lambda)^2/j^2 \ll (2m\lambda f_0)/j$, then $r_m = [(2m\lambda f_0)/j]^{1/2}$. While vertical plane wave is incoming, every $r_m$ corresponds to a plane wave in Eq. (5), then the focal length of the BOL is given as $f_0 = r_m^2 j/(2m\lambda_d)$, here to $m$ is the maximum $N$, the focal length is

$$f_0 = r_N^2 j/(2mN\lambda_d) = R^2 j/(2N\lambda_d) = R^2/(2M\lambda_d), \qquad (6)$$

From Eq. (6) $j$ does not affect the focal length of BOL when changed. To make the three waves have same focal length, Eq. (7) should be considered:

$$f_\lambda = \lambda_d \lambda^{-1} f_0, \qquad (7)$$

For harmonic diffractive lens

$$f_{m,\lambda} = p\lambda_d(k\lambda)^{-1} f_0, \qquad (8)$$

where $p$ is integer, $k$ is diffractive order.

For the purpose of obtaining maximum diffractive effect, etching step is decided as 8, etching depth is given as $d = \lambda_d/[8(n-1)]$, here $n$ is refractive index of the diffractive material. According to radius of rings, the minimum line-width can be gotten from:

$$\delta = r_n - r_{n-1} = [(2n\lambda f)/j]^{1/2} - \{[2(n-1)\lambda f]j\}^{1/2}, \qquad (9)$$

The phase function of rotational symmetric diffractive surface of BOL is expressed as

$$\Phi(r) = 2\pi\lambda^{-1}(A\lambda r^2 + G\lambda r^4 + \cdots), \qquad (10)$$

In Eq. (10), $A_\lambda$ is the second-phase coefficient to decide the value of paraxial focal power. For the BOL at specific wavelength, $A_\lambda$ is directly proportional to wavelength and used to correct system aberrations. $G_\lambda$ is the aspherical phase coefficients used to correct other orders of spherical aberrations of the system. Here we use the second-phase coefficient $A_\lambda$ to remove the secondary spectrum.

## 4 Simulation of long focal length diffractive-refractive lens

### 4.1 Longitudinal aberration of the system

A long telescope lens was designed with ZEMAX, an optical design software. It demanded that system focal length is $f = 450$ mm, $D = 100$ mm for maximum aperture, $2\omega \leqslant 2°$ for field angle. To meet up with the aerospace application, the waveband of spectrum should be at the range of 420.0~900.0 nm. In long focal length telescope three lenses would be used. The first lens was made of BK7 glass, the second lens was BOL with refractive index $n_B$, and the third lens was made of SF10 glass, focal lengths were calculated with Eq. (3). In the simulation, the focal length of BOL is $1.69\times 10^5$ mm, the structure of BOL is optimized as: number of ring strips is 104, minimum line width is 0.2404 mm, net length of the system is under 720 mm.

According to the principle of apochromats, the secondary spectrum met up with the technical requirement of the optical system. Spherical aberration and sinusoidal aberration were reduced by means of computer optimization.

The center field of the telescope was over corrected, there was no difference among the field 0.5 and 0.8 for three colors. There is no enough correction for the field 0.7, but this had no more effect on the secondary spectrum of optical system. This optimized system is featured that the two fields points get 0 aberration at 0.5 and 0.8.

Assuming the object is positioned at infinite distance stop points is at the sphere center behind the BOL. The simulation result of the optical system was shown in Fig. 1. From Fig. 1 it was known that the aberrations of lens in the telescope had been confirmed, the other parameters do not be used, correction aberration can be done by these parameters (not understandable, suggest for making some modification).

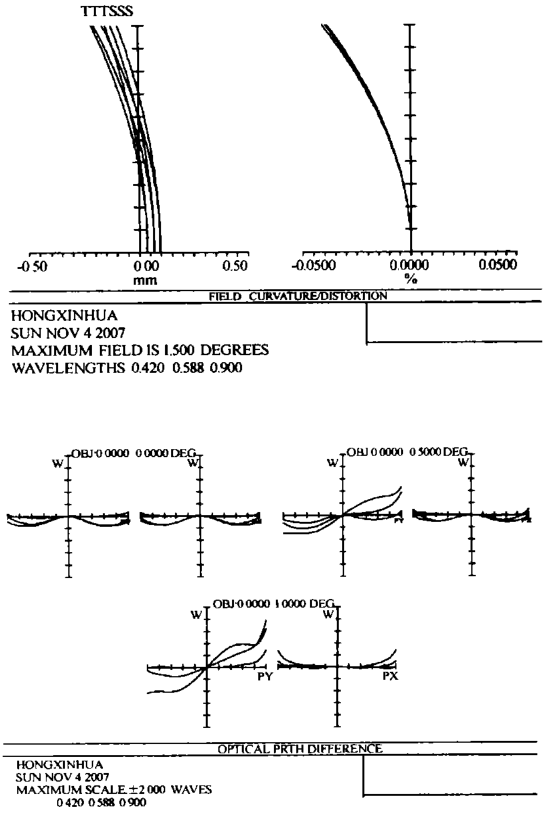

Fig. 1 Field curvature/distortion/OPD of the system

### 4.2 Modulation transfer function (MTF) of the system

MTF can be used to express characteristic frequency of ground imaging resolution of the system and show imaging quality of optical system. Usually high imaging quality optical instruments use to approximate by diffractive-limited method. The imaging results expressed by MTF of the system were shown in Fig. 2, the results were satisfied whatever sagittal plane *(S)* or meridional plane *(T)*. Line resolution was shown with SF, unit is $(\mathrm{mm})^{-1}$.

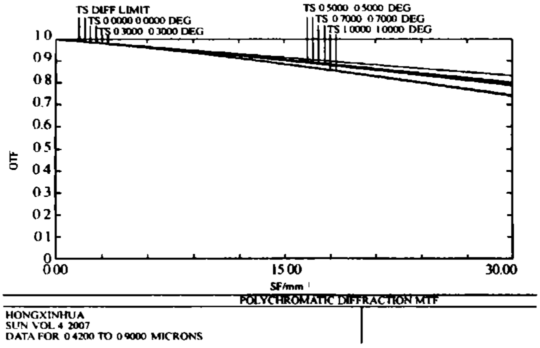

Fig. 2　MTF of the system

From Fig. 2 we can see, simulation results of the lens were agree with design index of the system. It reached to the bottomline of the diffractive limit in 0. 5m field. MTF was more than 0. 6 when frequency reached up to 30 SF at 1 m field. When the focal power was fixed, other parameters were used to correct distortion and other aberrations. Compared to other common telescopes, the system is compact and lightweighted.

## 5　Conclusions

According to the lens simulation results on ZMAX, it can be concluded that the secondary spectrum of lens can be reduced to a very low scale by using of hybrid diffractive-refractive methods for aerospace telescope. The size and whole weight of the telescope are reduced obviously relative to the traditional refractive system. In addition, the simulation results show that the MTF of such kind of system keeps a high value in all the fields of view, which means it can be both applied in aerospace telescope system and other research fields with high image quality, lightweight and compact structure required.

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